Nuclear giant resonances*

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This talk presents the recent status of theoretical and experimental studies of giant resonances in nuclei with the emphasis on: (1) charge-exchange Gamow-Teller resonance, (2) multiple-phonon resoanances, (3) giant dipole resonances in highly excited nuclei, and (4) pygmy dipole resonances in neutron rich nuclei. In particular, the description of these resonances within the framework of the phonon damping model is discussed in detail.

INTRODUCTION

Giant resonances (GR) are fundamental modes of nuclear excitations at high frequencies. The best-known one of them is the giant dipole resonance (GDR), which was observed in photo nuclear reactions 56 years ago and is described as the collective motion of protons against protons according to the simplest theoretical model by Goldhaber and Teller. The collective model of nucleus indicates that the nucleus should be studied in terms of normal modes, many of which are vibrational modes. Since the GDR is a giant vibration, by studying the GDR we learn a great deal about how the single-particle motion is coupled to vibrations, hence about the nuclear structure itself. Many other types of GR were measured later. They include giant multipole resonances such as the E0 giant monopole (GMR), E2 giant quadrupole (GQR), isoscalar E3 resonances seen in (e, e') and (α, α') reactions, magnetic M1 resonances GDR observed in (p, p') reactions, charge -exchange Gamow-Teller resonance extracted in (p, n) reactions. Recently the isoscalar GDR, the multiple-phonon GR, and the GDR in highly excited nuclei (hot GDR) were also observed. With the development of research in neutron-rich nuclei, new modes of excitations such as soft-dipole in neutron-halo nuclei, pygmy resonances in neutron-skin nuclei, and their coupling to GDR were also studied.

In this talk I will present a simple model, called phonon-damping model (PDM), which turns out to be successful in describing simultaneously many of these resonances, including the GDR in hot nuclei, double GDR (DGDR), Gamow-Teller resonance (GTR) in stable nuclei, as well as pigmy dipole resonances (PDR) in neutron-rich nuclei.

THE PHONON DAMPING MODEL

The PDM has been proposed in 1998 in Ref. [1], and developed further in a series of papers [2, 3]. According to the PDM the propagation of the GR phonon is damped due to coupling to quasiparticle field. The final equation of the Green function for the GR propagation has the form [3]

$$G_{\lambda i}(E) = \frac{1}{2\pi}\frac{1}{E-\omega_{\lambda i}-P_{\lambda i}(E)} \ , \tag{1}$$

where the explicit form of the polarization operator $P_{\lambda i}(E)$ is

$$P_{\lambda i}(E) = \frac{1}{\hat{\lambda}^2}\sum_{jj'}[f_{jj'}^{(\lambda)}]^2\left[\frac{(u_{jj'}^{(+)})^2(1-n_j-n_{j'})(\epsilon_j+\epsilon_{j'})}{E^2-(\epsilon_j+\epsilon_{j'})^2} - \frac{(v_{jj'}^{(-)})^2(n_j-n_{j'})(\epsilon_j-\epsilon_{j'})}{E^2-(\epsilon_j-\epsilon_{j'})^2}\right]. \tag{2}$$

Here $u_{jj'}^{(+)} = u_j v_{j'} + u_{j'} v_j$, $v_{jj'}^{(-)} = u_j u_{j'} - v_j v_{j'}$ are combinations of Bogolyubov (u, v) factors, ϵ_j are quasiparticle energies, and n_j are the temperature-dependent quasiparticle-occupation numbers, whose form is close to that given by the Fermi-Dirac distribution. The phonon damping $\gamma_{\lambda i}(\omega)$ (ω real) is obtained as the imaginary part of the analytic continuation of the polarization operator $P_{\lambda i}(E)$ into the complex energy plane $E = \omega \pm i\varepsilon$:

$$\gamma_{\lambda i}(\omega) = \frac{\pi}{2\hat{\lambda}^2}\sum_{jj'}[f_{jj'}^{(\lambda)}]^2\Big\{(u_{jj'}^{(+)})^2(1-n_j-n_{j'})[\delta(E-\epsilon_j-\epsilon_{j'})-\delta(E+\epsilon_j+\epsilon_{j'})]-$$

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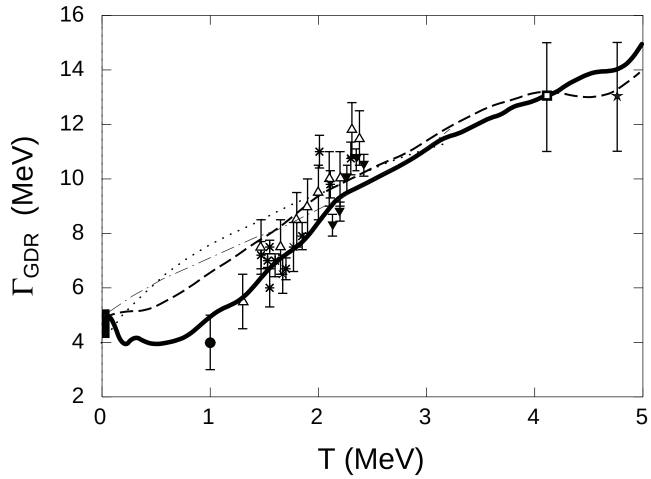

FIG. 1: GDR width Γ_{GDR} as a function of temperature T for ^{120}Sn. The dashed and solid lines show the PDM results obtained neglecting and including thermal pairing gap, respectively. The predictions by two versions of the thermal shape-fluctuation model are shown as the dash-dotted [4] and thin dotted [5] lines, respectively. The experimental data in taken from Refs. [6].

$$(v_{jj'}^{(-)})^2(n_j - n_{j'})[\delta(E - \epsilon_j + \epsilon_{j'}) - \delta(E + \epsilon_j - \epsilon_{j'})]\Big\}. \tag{3}$$

The energy $\bar{\omega}$ of giant resonance (damped collective phonon) is found as the pole of the Green's function (1):

$$\bar{\omega} - \omega_{\lambda i} - P_{\lambda i}(\bar{\omega}) = 0 \ . \tag{4}$$

The width Γ_λ of giant resonance is calculated as twice of the damping $\gamma_\lambda(\omega)$ at $\omega = \bar{\omega}$, i.e.

$$\Gamma_\lambda = 2\gamma_\lambda(\bar{\omega}), \tag{5}$$

where $\lambda = 1$ corresponds to the GDR. The line shape of the GDR is described by the strength function $S_{\mathrm{GDR}}(\omega)$, which is derived as:

$$S_{\mathrm{GDR}}(\omega) = \frac{1}{\pi}\frac{\gamma_{\mathrm{GDR}}(\omega)}{(\omega - \bar{\omega})^2 + \gamma^2_{\mathrm{GDR}}(\omega)} \ . \tag{6}$$

COMPARISON OF THEORETICAL PREDICTIONS WITH EXPERIMENTAL DATA

The PDM has been proved to be quite successful in the description of the width and the shape of the GDR as a function of temperature T and angular momentum J. An example is shown in Fig. 1. The PDM has resolved the long-standing problem with the electromagnetic (EM) cross sections of the DGDR in ^{136}Xe and ^{208}Pb, in which the prediction by the non-interacting phonon picture underestimated significantly the observed DGDR cross sections by the LAND collaboration. The prediction using the strength functions obtained within PDM [7] is given in Fig. 2 in comparison with the latest results of data analyses by LAND collaboration [8]. The agreement between the PDM prediction and the data is remarkable.

Shown in Fig. 3 is the prediction of [9] within two versions of PDM, called PDM-1 (thin solid line), and PDM-2 (thick solid line) (for the details see Refs. [1, 2]) for the GTR in ^{90}Nb in comparison with the result obtained within a microscopic theory which explicitly includes coupling to $2p2h$ configurations in terms of two-phonon configurations (dotted line) [10], and the experimental data (data points with errorbars) [11]. Again, the agreement between theory and experiment is quite reasonable. Shown in Fig. 4 are the photoabsorption cross sections $\sigma(E_\gamma)$, which have been obtained within PDM for ^{16,18}O and ^{40,48}Ca [3]. The shapes of the calculated photoabsorption cross sections are found in overall reasonable agreement with available experimental data [12] The fractions of the energy-weighted sum (EWS) of strength exhausted by the low-energy tail of GDR are shown in Figs. 5. The trend obtained

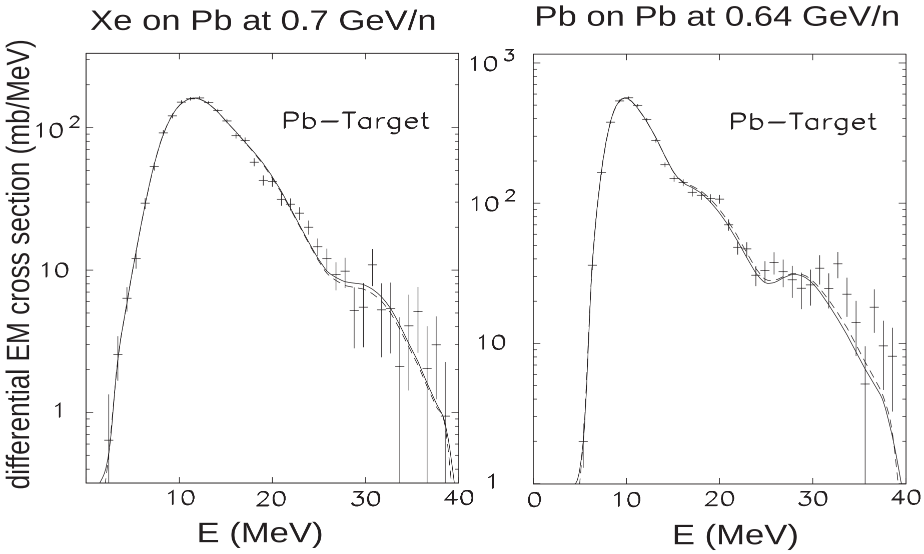

FIG. 2: EM cross sections of GDR and DGDR for ^{136}Xe and ^{208}Pb. The solid lines are theoretical predictions, in which the DGDR strength functions within PDM are used. The data points are results of the LAND collaboration [8]. The dashed lines show the best fit using χ^2. The theoretical results have been folded with the detector response by K. Boretzky [8].

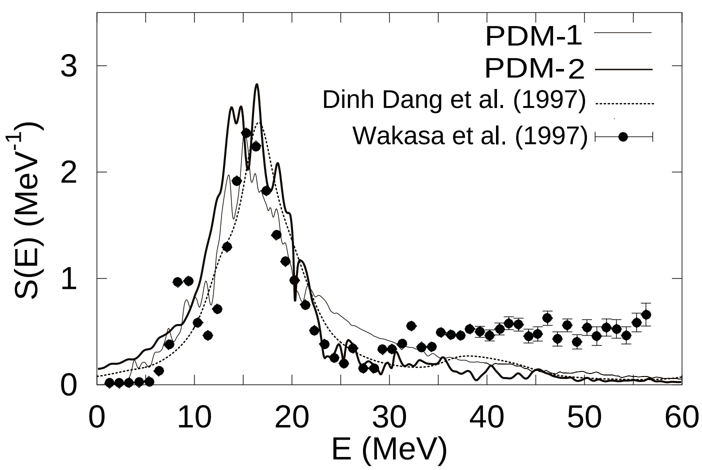

FIG. 3: Strength functions of the GTR in 90Nb. See text for the notation.

within PDM for oxygen isotopes reproduces the one observed in the recent experiments at GSI [13], which shows a clear deviation from the prediction by the cluster sum rule (CSR). The agreement between the PDM prediction and the experimental data for the photoabsorption cross sections as well as for the EWS of PDR strength suggests that the mechanism of the damping of PDR is dictated by the coupling between the GDR phonon and noncollective *ph* excitations rather than by the oscillation of a collective neutron excess against the core. Strong pairing correlations also prevent the weakly bound neutrons to be decoupled from the rest of the system [14]. Only when the GDR is very collective so that it can be well separated from the neutron excess, the picture of PDR damping becomes closer to the prediction by the CM.

CONCLUSION

The PDM is a simple yet microscopic model, which can describe rather well various resonances and has resolved several long standing problems including the width and shape of the hot GDR, the electromagnetic cross section of the DGDR, the spreading (quenching) of the GTR. It also predicts the

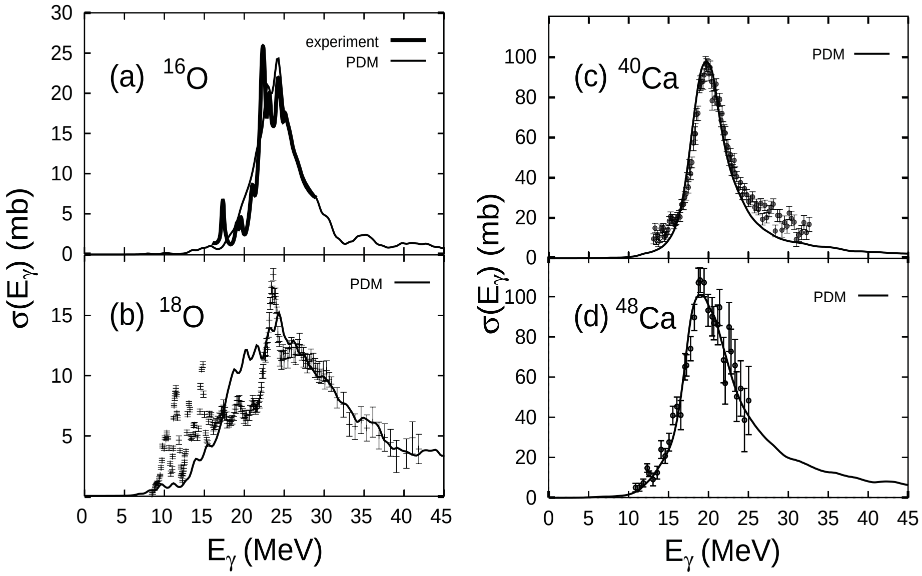

FIG. 4: Photoabsorption cross sections for ^{16,18}O and ^{40,48}Ca obtained within PDM in comparison with experimental data [12].

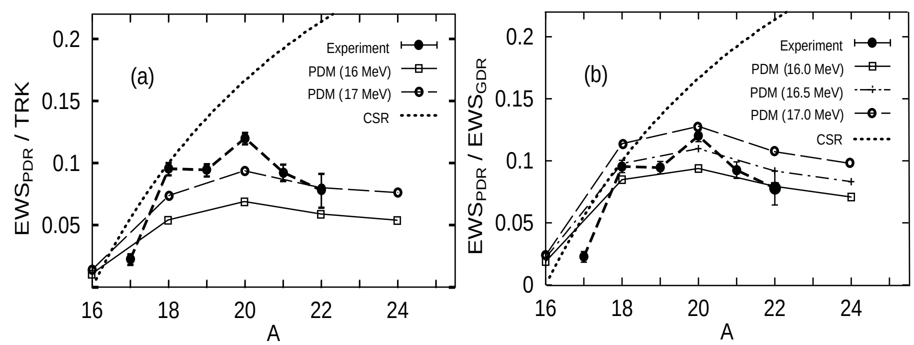

FIG. 5: EWS of PDR strength up to excitation energy $E_{\max}$ for oxygen isotopes. Results obtained within PDM with $E_{\max}$ = 16, 16.5, and 17 MeV are displayed as open boxes connected with solid line, crosses connected with dash-dotted line, and open circles connected with thin dashed line, respectively. In (a) the PDM results are shown in units of Thomas-Reich-Kuhn sum rule (TRK), while in (b) they are in units of the total GDR strength integrated up to 30 MeV. Experimental data (in units of TRK), obtained with $E_{\max}$ = 15 MeV [13] are shown by full circles connected with thick dashed line. The dotted line is the prediction by the cluster sum rule (CSR) (in units of TRK).

PDR in neutron-rich nuclei and the DGDR in hot nuclei.

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